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STRAIN RATE AND STRAIN RATE HISTORY EFFECTS IN TWO MILD STEELS.(U)
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Results are presented of a series of experiments performed with two steels to investigate the dependence of flow stress on strain rate and its history. For this purpose quasi-static, dynamic and incremental strain rate tests were conducted on SAE 1020 hot-rolled steel and SAE 1018 cold-rolled steel at room temperature. It is shown that while the flow stress of both steels exhibits a significant strain rate sensitivity, the effect of strain rate history is relatively small in comparison with that generally found in fcc and hcp metals. A comparison is made with results of the work of other investigators.

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STRAIN RATE AND STRAIN RATE HISTORY EFFECTS IN TWO MILD STEELS

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TECHNICAL REPORT
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Abstract

Results are presented of a series of experiments performed with two steels to investigate the dependence of flow stress on strain rate and its history. For this purpose quasi-static, dynamic and incremental strain rate tests were conducted on SAE 1020 hot-rolled steel and SAE 1018 cold-rolled steel at room temperature. It is shown that while the flow stress of both steels exhibits a significant strain rate sensitivity, the effect of strain rate history is relatively small in comparison with that generally found in fcc and hcp metals. A comparison is made with results of the work of other investigators.

Introduction

Fundamental to an understanding of the plastic deformation of metals is the determination of the influence of the prior strain, strain rate and temperature on the stress level required for continued plastic flow. Furthermore, an understanding of strain rate history and temperature history dependence will aid in the development of constitutive laws needed to predict the behavior of metals in applications involving varying load conditions. Numerous investigators over the years have studied history effects, and the most useful experiment developed thus far for this purpose involves the imposition during the course of deformation of sudden increments in temperature or strain rate. In the earliest experiments, rapid changes in temperature rather than strain rate were imposed (1-3). This is probably because changes in temperature are easier to effect during loading than are changes in strain rate. Furthermore, a convincing demonstration of the effects produced by a rapid change in strain rate frequently requires an increment of six or seven orders of magnitude. Thus the first incremental strain rate experiments (outside the creep range) were not performed until 1964 by Lindholm (4), who imposed alternately a quasi-static strain rate of $10^{-4}s^{-1}$ and a dynamic rate of $10^{3}s^{-1}$ on specimens of aluminum. However, in these tests, as in others carried out shortly thereafter (5-7), complete unloading of the specimen occurred at every change in strain rate. Campbell and Dowling (8) were the first to impose an increment in strain rate with no prior unloading. They tested specimens of copper and aluminum, both fcc metals; their highest strain rate was 90 s^{-1}. Nicholas (9) tested specimens of steel, as well as other metals, in torsion using a hydraulic machine. His strain rate increments were imposed at a shear strain of about 2% and carried the strain rate from $10^{-4}s^{-1}$ to $25\ s^{-1}$. More recently, Eleiche and Campbell performed incremental strain rate tests on specimens of three metals including a mild steel (10). The specimens were thin-walled tubes loaded in shear at a quasi-static strain rate of $6 \times 10^{-3}s^{-1}$ and a dynamic rate of $1200s^{-1}$. The increments in strain rate were imposed at shear strains of 8, 20 and 34%.

From results obtained thus far for various metals, it is possible to construct stress-strain curves which show schematically the material behavior at different strain rates as well as the response which follows a sharp increment in strain rate. The schematic diagram in Figure 1 represents the material response typical of fcc metals. Although the present experiments were performed with steel, a bcc metal, and hence in some respects produce quite different results, it is useful to define certain quantities on the basis of this figure. The highest curve in the figure represents the behavior of a specimen deformed at a constant strain rate in shear, $\dot{\gamma}_r$. If a similar specimen were deformed at a lower constant strain rate, $\dot{\gamma}_i$, its behavior would be represented by the lower curve in the figure. In an incremental strain rate test the specimen is deformed initially at the strain rate $\dot{\gamma}_i$ then, at some value of strain, γ_i, and with no unloading, the strain rate is increased abruptly to $\dot{\gamma}_r$. Corresponding to this increment in strain rate, the stress jumps by the amount $\Delta\tau_s$ before plastic flow continues at the higher strain rate. It is generally believed that the stress increment $\Delta\tau_s$ provides a better measure of strain rate effects than does the entire stress difference $\Delta\tau_s + \Delta\tau_h$. The stress difference $\Delta\tau_h$ should represent the influence of history on the stress-strain curve, since the strains and strain rates at points C and F in the figure are substantially equal. Furthermore, since at the strain γ_i and for some strain thereafter plastic deformation at the strain rate $\dot{\gamma}_r$ takes place at two levels of flow stress, it is evident that flow stress is not a unique function of strain, strain rate and temperature. Beyond γ_i , the difference in stress levels, certainly in the case of fcc metals, diminishes as the deformation continues at $\dot{\gamma}_r$. This phenomenon is often termed a fading memory, since the flow stress is influenced more strongly by the more recent strain rate history than by the more distant past and since, after sufficient additional straining, the difference in stress levels approaches zero. Klepaczko and Duffy [11] showed that the magnitude of the additional strain required in order that the memory be completely erased depends on the previous strain rate history, at least in the case of fcc metals. For the hcp and the bcc metals, including steel, the effects of strain rate history are not well understood (12,13)

In the present investigation incremental strain rate tests were performed on polycrystalline specimens of two low carbon steels, one hot-rolled and the other cold-rolled. The purpose of the investigation was to determine the influence of strain rate and strain rate history on two bcc metals of nearly identical chemical composition but of quite different forming histories and to compare the results with those typically obtained with fcc and hcp metals.

Apparatus

The present experiments were performed with the stored-torque Kolsky bar shown schematically in Figure 2a. This bar is an adaptation to torsional loading of Kolsky's original compressional split-Hopkinson bar. In its present configuration, the torsional Kolsky bar provides the means in the same apparatus for loading either entirely at a high strain rate or entirely at a low rate. Furthermore, it is possible during quasi-static loading to increase the strain rate suddenly and with no prior unloading. Details of the apparatus have been presented in a previous publication [13], but a brief description follows.

The high (dynamic) strain rates in the present experiments are achieved through the sudden release of a stored-torque at one and of the Kolsky bar, thus initiating a torsional pulse, Figure 2. Electric resistance strain gages at G_1 measure the magnitude of this stored-torque whose sudden release is effected by fracturing a brittle breaker-piece which forms part of the clamp. Upon release of the torque, a sharp-fronted torsional loading pulse of constant amplitude (equal to half the stored torque) propagates down the bar toward the specimen. Simultaneously, an unloading pulse of equal magnitude propagates from the clamp toward the torque pulley. The mechanical impedance of the pulley is sufficiently large so the unloading pulse, after reflection from the pulley, reduces the torque in the incident bar to zero as it propagates toward the specimen. The duration of the loading pulse on the specimen, therefore, is the time required for a pulse to travel twice the distance along the bar between the clamp and the torque pulley. The rise-time of the loading pulse produced with the present apparatus is about 40 microseconds and the duration of the pulse was set at about 480 microseconds.

Strain gages are mounted on the incident and transmitter bars at G_2 and G_3 respectively, the former to measure the incident and reflected pulses and the latter the pulse transmitted through the specimen. Their location along the bars must meet two requirements. First, the gages at G_2 must be far enough from the specimens to avoid overlap between the incident and reflected pulses, and in addition G_2 and G_3 must be at the same distance from the specimen if Lindholm's method (4) is to be used to convert their outputs immediately into a stress-strain diagram for the specimen.

The apparatus just described is employed as well for the quasi-static tests on specimens having precisely the same dimensions as those used in the dynamic tests. The quasi-static tests require that the further end of the transmitter bar be twisted slowly while the incident bar is prevented from turning by a set of one-way stops located just ahead of the clamp used to store the torque. The torque imposed on the specimen during a quasi-static test is measured by the strain gages mounted at G_3 on the transmitter bar and which thus are used both in the static and dynamic tests. Strain in the specimen is measured by finding the difference in angular rotation between the ends of the specimen. For this purpose two linear variable differential transformers (LVDT's) are located immediately to either side of the specimen. These LVDT's are rigidly mounted, while fine tungsten wires connected to their cores are wound around the circumference of the elastic bars. Hence, during loading of the specimen, the angular displacement of the bars is converted to a linear displacement of the LVDT cores. The output signals of the LVDT's are connected electrically to produce a single signal proportional to the net relative displacement between the ends of the specimen. Thus the instrumentation provides a measure of the relative angular displacement as a function of applied torque, which is easily converted to a shear stress-shear strain diagram by a proper calibration, taking into consideration the specimen geometry, the strain gage sensitivity and the elastic response of the short portion of the Kolsky bar lying between the LVDT's.

The incremental strain rate experiment is effected by combining the static and dynamic loading capabilities of the apparatus described above. For this purpose, the specimen is first loaded quasi-statically to a pre-determined plastic strain γ_i , whereupon the previously stored torque is released to provide a constant amplitude loading pulse which is superimposed upon the quasi-static load. By this means the imposed strain rate is increased by a factor of approximately 10^6 or 10^7 depending on the initial quasi-static strain rate and on the magnitude of the stored torque.

One should point out that the Kolsky bar provides an important advantage in incremental strain rate tests: the transmitted signal is a measure not of the total stress in the specimen, but of the excess stress imposed by the stress pulse above that existing as a result of loading at the quasi-static strain rate. Thus one obtains directly the stress increment due to the change in strain rate rather than having to rely on finding a small difference between two large numbers.

Specimens

The specimens were machined in the form of thin-walled tubes with the nominal dimensions shown in Figure 3. The material was 25 mm bar stock, in one case 1018 cold-rolled steel (CRS) and in the other 1020 hot-rolled steel (HRS). The critical dimensions of each specimen, namely the wall thickness, the inside diameter and the gage length, were measured using fixtures specially designed for that purpose. In particular, accurate measurements of the wall thickness are essential to insure quality control of the specimens; a small error in this dimension produces large errors in data reduction. Alignment of the specimen for cementing within the Kolsky bar was assured by the use of concentric reliefs at the end of each bar. The chemical composition of the two materials is given in Table I.

No heat-treatment was employed either before or after machining. The typical grain size was 15 to 17μ, giving 20 or 25 grains radially across the wall of the specimens, equivalent to 40,000 or 50,000 grains in a typical cross-section.

Results

Stress-strain curves at a quasi-static strain rate of $5 \times 10^{-4}\ s^{-1}$, a dynamic strain rate of $10^{3}\ s^{-1}$ and those resulting from incremental strain rate tests between these two strain rates are given in Figures 4 and 5 for HRS and for CRS, respectively. It is evident that for both steels, the strain rate has a significant effect on flow stress. This is consistent with results of other investigators [9,10,14,15].

For the HRS (Figure 4), a distinct upper and lower yield point is apparent in the all-dynamic flow curve, it is present also, but to a lesser degree in the quasi-static flow curve. On the other hand, the incremental strain rate tests show no evidence of an upper and lower yield point. There is however, an abrupt increase in the stress from the quasi-static curve almost to the stress level of the all-dynamic flow curve. In nearly all cases, the stress-strain curve following the strain rate increment quickly joins the all-dynamic curve, implying no "memory" effect in sharp contrast to the results of Senseny et al. [13] for fcc and hcp metals, who found that the stress after the increment in strain rate was significantly lower than the all-dynamic flow stress and approached it only gradually with further straining. Thus, it appears that strain rate history has significantly less effect on flow stress in low carbon HRS, a bcc metal, than in aluminum or copper, fcc metals, or magnesium or zinc, which are hcp metals [13]. One should note also the contrasting bahvior, as for upper and lower yield points, with the results of Frantz and Duffy [16]. For an 1100-0 aluminum they found, as expected, no upper and lower yield point for tests at a constant strain rate whether quasi-static or dynamic. However, the phenomenon did occur following an increment in strain rate, which is precisely the opposite of the results in steel.

In the case of CRS (Figure 5), no upper and lower yield points are evident. As expected, the work-hardening rate for this material is lower than for HRS. Furthermore, the strain rate sensitivity of the CRS is somewhat less than that of HRS; and again the incremental flow curve very quickly joins the all-dynamic flow curve, so that strain rate history effects again appear to be small.

An interesting result of the tests with CRS is the material instability which occurs after about 10 percent plastic strain at the dynamic strain rate. For this material, the word-hardening rate at the high strain rate remains positive only to a strain of about 10%. At about that value the flow stress attains a maximum after which it decreases steadily. This occurs in the all-dynamic tests and also in the incremental strain rate tests, and is associated with the formation of a non-homogeneous state of strain within the specimen's gage length: a band of very high shear strain going around the circumference of the specimen. In torsional Kolsky tests, shear bands of this nature are easily detected by scribing fine lines axially along the specimen's internal surface before testing. Fine axial lines of this sort generally are scribed on all specimens tested in a torsional Kolsky bar to insure that all results are based on homogeneously deforming specimens. For the CRS, these lines revealed the presence of shear bands. These shear bands form the subject of a separate investigation which was conducted to determine their cause [18]. It is significant to note that no such bands were found in the deformation of the HRS.

Various measures have been used as gages of the strain rate sensitivity of a material. One possible measure is the ratio τ_2/τ_1 , where τ_2 and τ_1 are respectively the values of flow stress at the same shear strain obtained in tests at two different strain rates; in the present instance $\dot{\gamma}_2 = 10^3\ s^{-1}$ and $\dot{\gamma}_1 = 5.10^{-4}\ s^{-1}$. Values of τ_2/τ_1 and μ_{12} based on the results of the present experiments are plotted against shear strain in Figs. 6 and 7, where they are compared with those of other investigators [9,10,14].

Another measure of strain rate sensitivity is given by

$$\mu_{12} = \frac{\partial\tau}{\partial \ell n\dot{\gamma}} \approx \frac{\tau_2 - \tau_1}{\ell n\dot{\gamma}_2/\dot{\gamma}_1} ,$$

sometimes referred to as the apparent strain rate sensitivity, as opposed to the true or intrinsic strain rate sensitivity which is defined as

$$\bar{\mu}_{12} = \frac{\tau_j - \tau_1}{\ell n\ \dot{\gamma}_2/\dot{\gamma}_1} ,$$

where τ_j is the flow stress at $\dot{\gamma}_2$ immediately following an increment in strain rate from $\dot{\gamma}_1$. The advantage of using μ_{12} (or $\bar{\mu}_{12}$) comes when deformation on the microscale is governed by a thermally-activated mechanism. In that case, if the energy of activation is a linear function of the shear stress, then the apparent activation volume is given by

$$v^* = \frac{kT}{\bar{\mu}_{12}}$$

where k is Boltzmann's constant and T is the temperature in degrees absolute. According to this formula, present results give a value of v^*/b^3 , where b is the Burger's vector, slightly greater than 30. This compares to a value of about 50 obtained by Eleiche and Campbell in similar tests (10), and to the value of 20 quoted by Conrad from entirely different types of tests (17). However, Conrad's value is for a steel at low temperature. (See Table II)

In every case, for the data reported here, the apparent strain rate sensitivity is greater than the true strain rate sensitivity, although the difference is not very large. Implicit in its definition, the apparent strain rate sensitivity includes the effect of strain rate history so that present results imply that strain rate history effects are not of great consequence in the deformation of these mild steels, in spite of their relatively large strain rate sensitivities.

A comparison of present results with those of Eleiche and Campbell (10) shows about the same strain rate sensitivity. However, with further straining following an increment in strain rate, the results appear quite different. Eleiche and Campbell show that flow stress following an increment in strain rate is significantly greater than would be achieved for the same strain in an all-dynamic test. In other words, strain rate history appears to be of consequence to the subsequent flow stress in the results of Eleiche and Campbell but not in the present results.

Conclusions

The flow stress in shear of two mild steels has been determined at a quasi-static and a dynamic strain rate. The two steels are similar in chemical composition but differ in that one is hot-rolled and the other cold-rolled. As a result of this difference in the manufacturing processes, the stress-strain curves of specimens of these two steels are quite different. As expected, during quasi-static straining the cold-rolled steel shows a higher initial yield stress than does the hot-rolled steel, but subsequently has a low strain-hardening rate,whereas that of hot-rolled steel is quite large. Furthermore, hot-rolled steel may show a small upper and lower yield stress. Dynamically, the upper and lower yield stress in hot-rolled steel is quite pronounced, but the two steels have nearly the same strain-hardening rates.

Turning to strain rate sensitivity, it is evident that the flow stress of mild steel increases relatively rapidly with an increase in strain rate, at least as compared to results obtained in previous investigations with fcc metals. This is consistent with the results of other investigators. Hot-rolled steel shows a somewhat greater strain rate sensitivity than does the cold-rolled. Strain rate history effects in both steels, as determined by incremental strain rate tests, appear to be small. Ultimately, this may simplify the representation of the mechanical behavior of mild steel by means of constitutive equations. The strain rate sensitivities of the two steels are calculated as a function of strain. In cold-rolled steel it remains approximately constant, but decreases with quasi-static prestrain in hot-rolled steel.

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TABLE 1

Chemical Composition of Test Materials in Precent

	C	Mn	P	S
1018 CRS	.18	.71	.020	.022
1020 CRS	.26	.50	.017	.029

TABLE II

Strain Rate Sensitivities

HRS

		$\gamma_1 = 5 \times 10^{-4} s^{-1}$			$\gamma_2 = 10^3 s^{-1}$		
γ (%)	τ_2/τ_1	τ_j/τ_1	μ_{12} (MPa)	μ_{12}/τ_1	$\bar{\mu}_{12}$ (MPa)	$\bar{\mu}_{12}/\tau_1$	v^*/b^3
3	1.96	1.92	10.27	0.066	9.78	0.063	27.3
5	1.73	1.69	9.37	0.050	8.82	0.047	30.3
10	1.62	1.45	9.24	0.043	6.75	0.031	39.6
15	1.54	1.51	8.82	0.037	8.34	0.035	32.0

CRS

		$\gamma_1 = 5 \times 10^{-4}$			$\gamma_2 = 10^3 s^{-1}$		
γ (%)	τ_2/τ_1	τ_j/τ_1	μ_{12} (MPa)	μ_{12}/τ_1	$\bar{\mu}_{12}$	$\bar{\mu}_{12}/\tau_1$	v^*/b^3
2.5	1.49	1.42	9.03	0.034	7.79	0.029	34.3
7	1.45	1.42	9.17	0.031	8.41	0.029	31.7
11		1.41			8.48	0.029	31.5

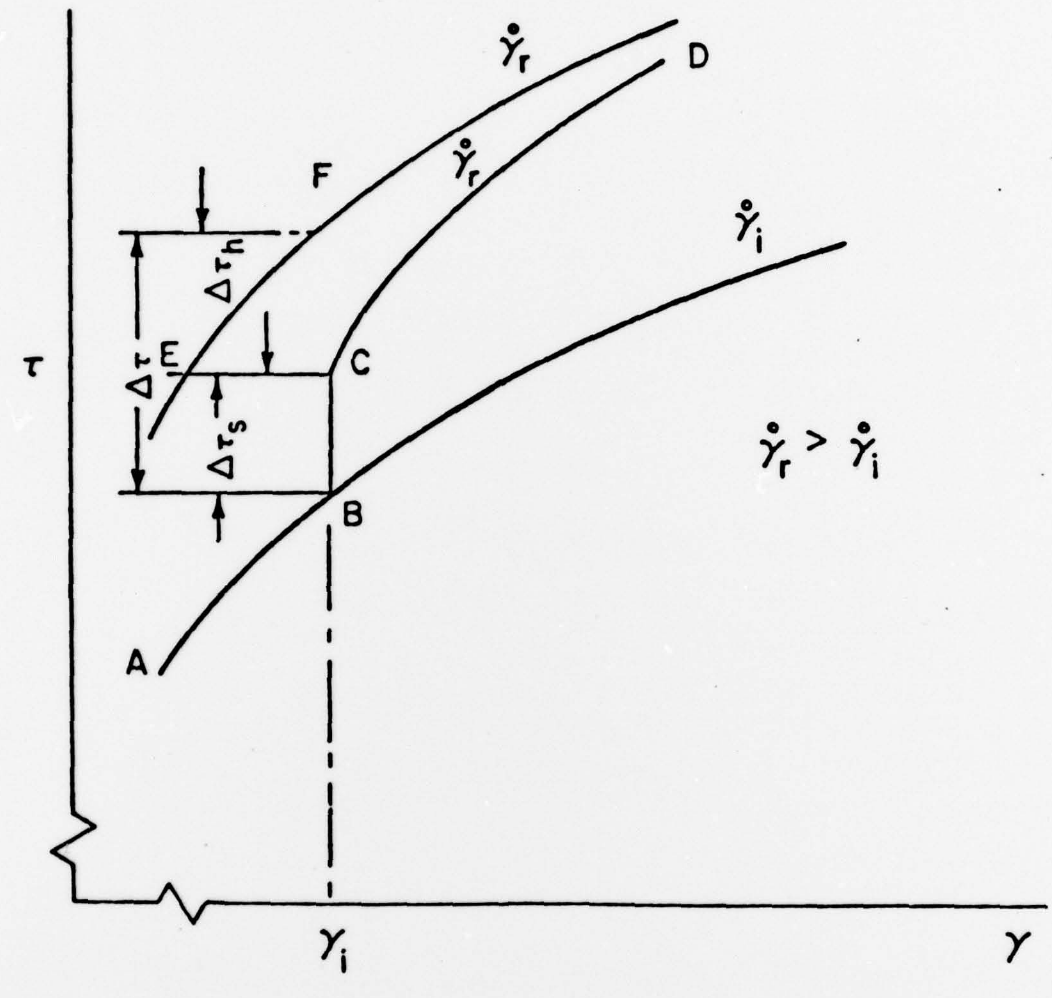
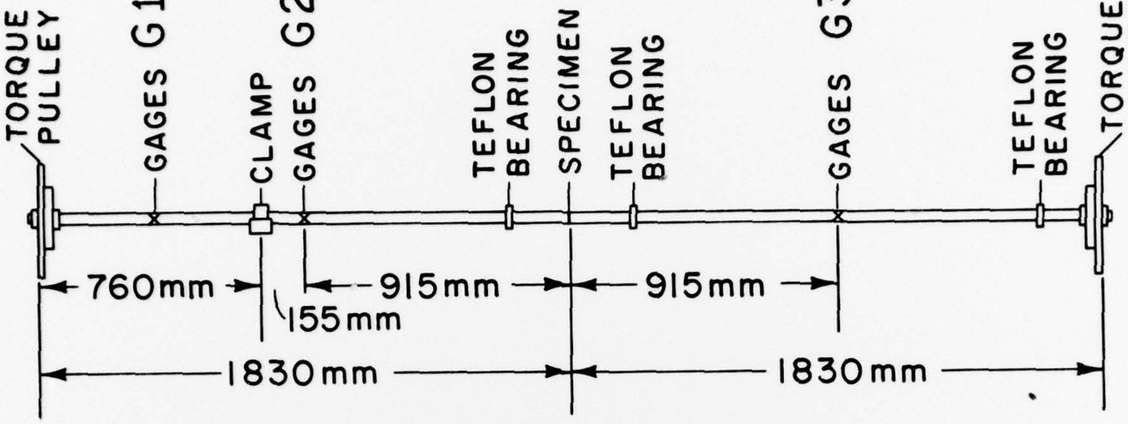
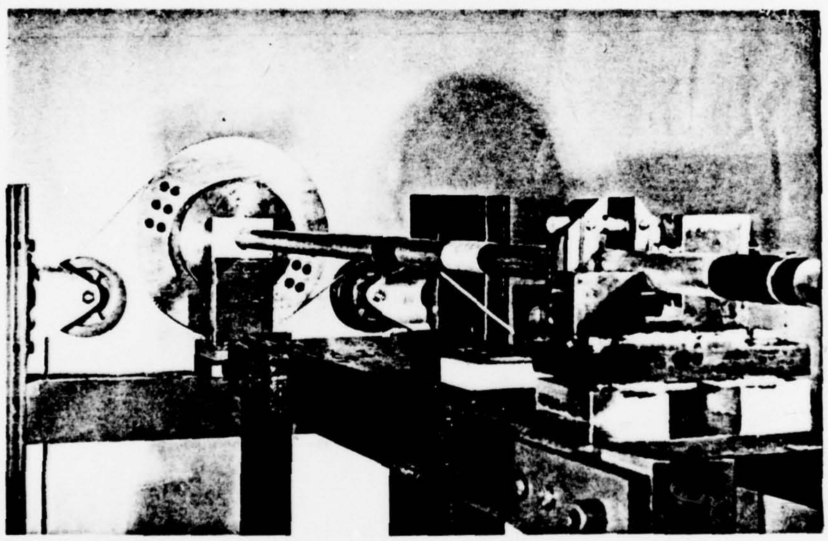


FIG. 1 SCHEMATIC REPRESENTATION OF FLOW CURVES RESULTING FROM CONSTANT STRAIN RATE LOADING AND FROM INCREMENTAL STRAIN RATE LOADING OF TYPICAL fcc METALS



(a)



(b)

FIG. 2 TORSIONAL KOLSKY BAR APPARATUS
(a) SCHEMATIC DIAGRAM OF COMPLETE KOLSKY BAR FOR STATIC, DYNAMIC AND INCRIMENTAL STRAIN RATE TESTING IN SHEAR
(b) PHOTO OF STORED TORQUE END SHOWING CLAMP AND ROTATIONAL STOPS

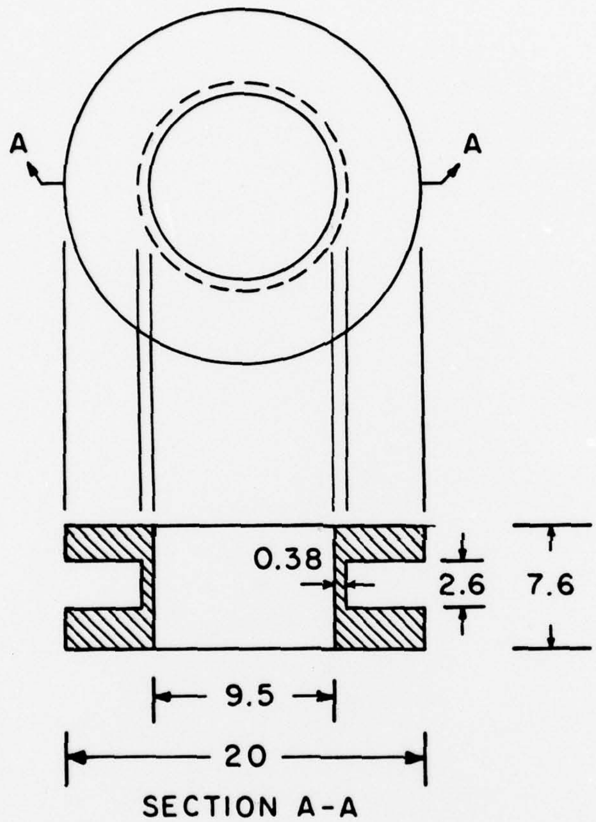


FIG. 3 DETAILS OF TORSIONAL SPECIMEN WITH INTEGRAL MOUNTING FLANGES. DIMENSIONS ARE IN MILLIMETERS.

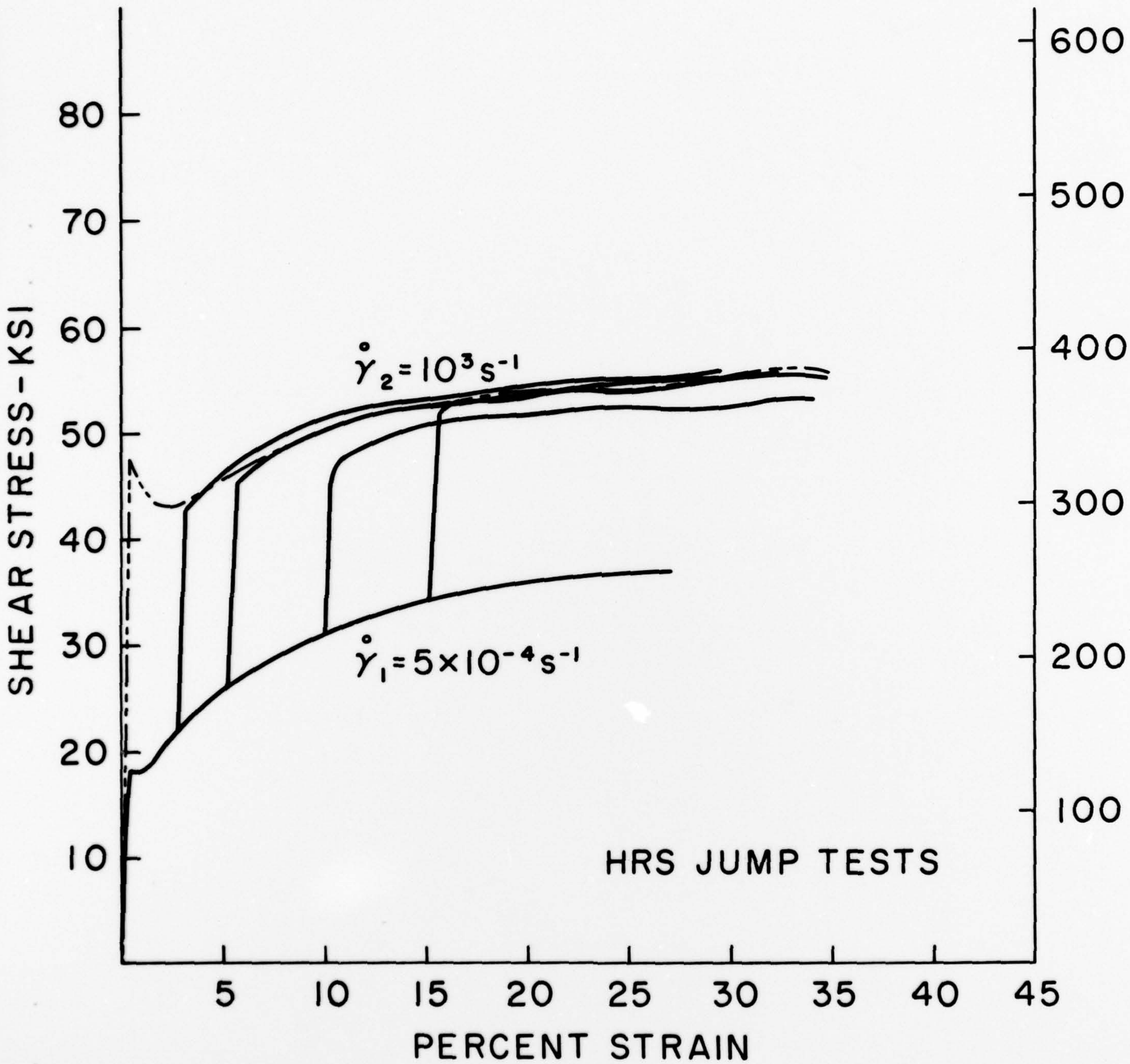


FIG. 4 RESULTS OF CONSTANT STRAIN RATE AND INCREMENTAL STRAIN RATE TESTS ON 1020 HOT ROLLED STEEL AT ROOM TEMPERATURE

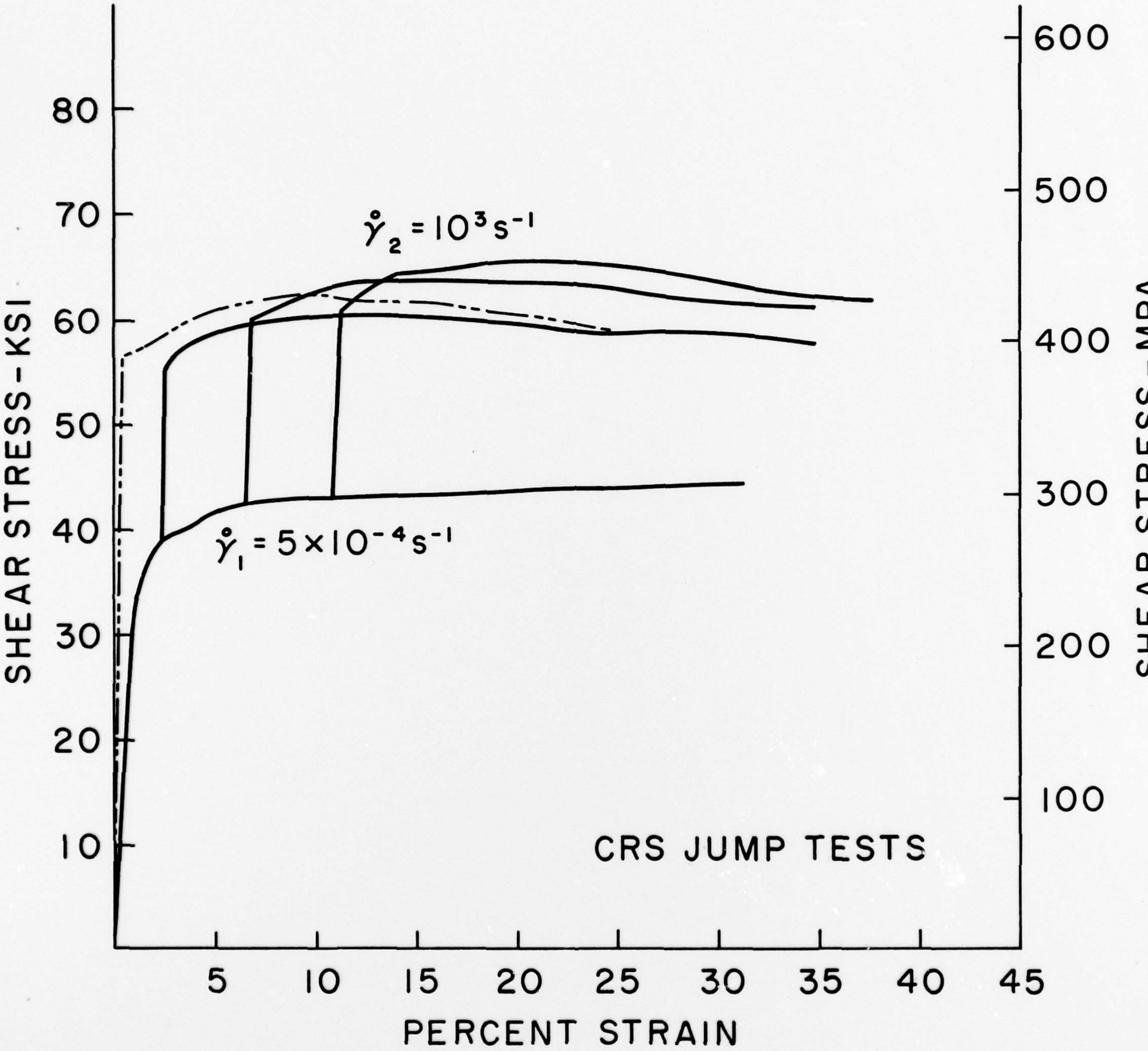


FIG. 5 RESULTS OF CONSTANT STRAIN RATE AND INCREMENTAL STRAIN RATE TESTS ON 1018 COLD ROLLED STEEL AT ROOM TEMPERATURE

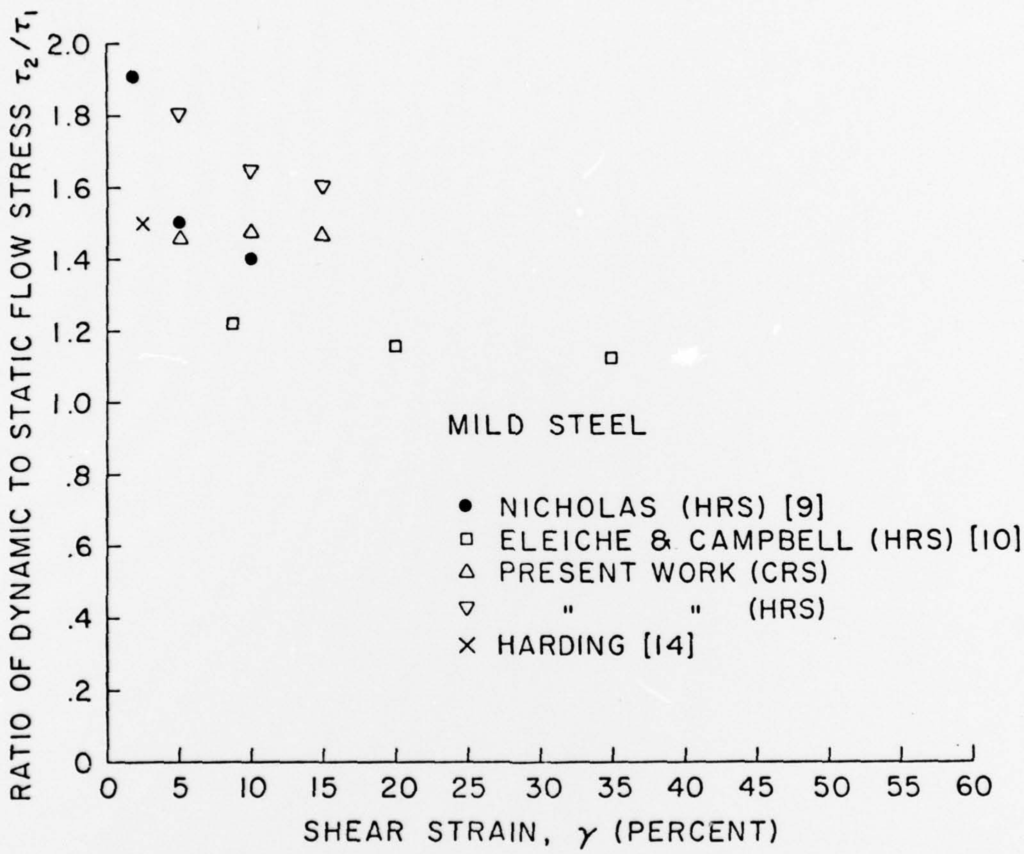


FIG. 6 RATIO OF DYNAMIC TO STATIC FLOW STRESS VS SHEAR STRAIN FOR MILD STEEL

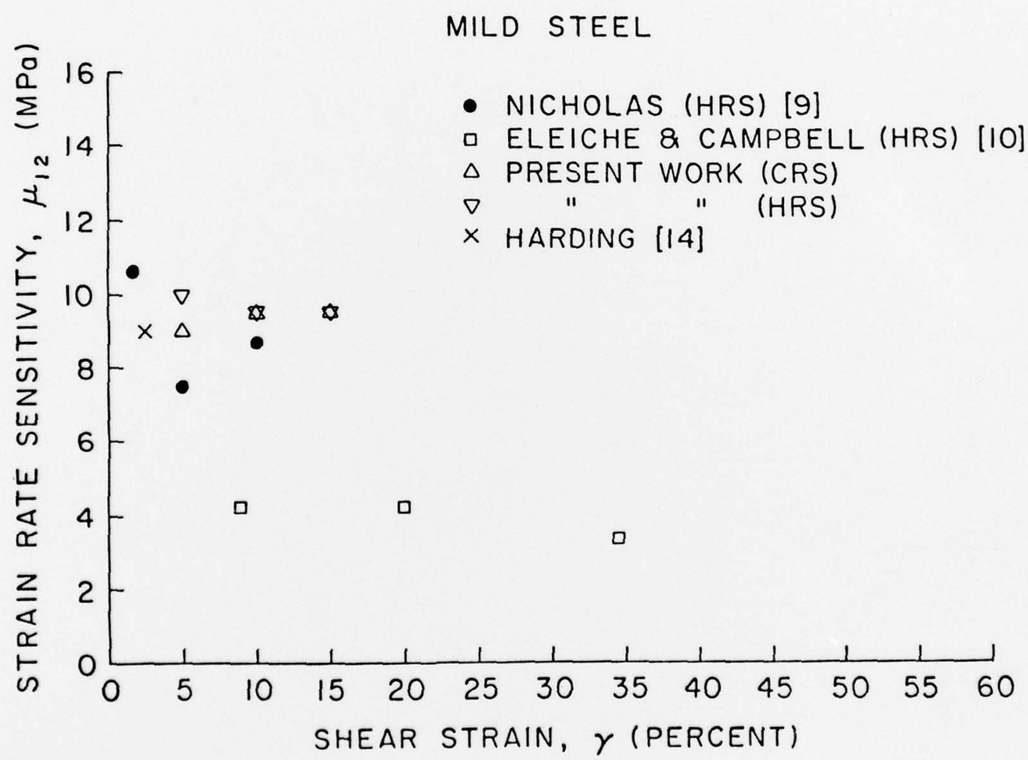


FIG. 7 STRAIN RATE SENSITIVITY VS SHEAR STRAIN FOR MILD STEEL